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Research article

On the design and assessment of regional air quality plans: The SHERPA approach

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ABSTRACT

Although significant progress has been made in Europe regarding air quality, problems still remain acute for some pollutants, notably NO_2 and Particulate Matter (fine and coarse fractions) in specific regions/cities. One issue regarding air quality management is governance, i.e. the selection of appropriate and cost effective strategies over the area controlled by policy makers. In this work we present a new approach to integrated assessment modelling focusing on regional and urban aspects. One of the key added values is spatial flexibility, namely the possibility to assess the contributions from different regions to air quality at any given location. The SHERPA tool is shown to be particularly helpful in addressing the following tasks: source allocation, governance and the assessment of scenario impacts. Application of the methodology over the London area for yearly averaged $PM_{2.5}$ concentrations demonstrates these features. Given that it is possible to use the SHERPA interface with other types of data, SHERPA can also be seen as a means to foster harmonization in the field of model evaluation.

1. Introduction

Although significant progress has been made in Europe regarding air quality in recent decades (EEA, 2015), problems still remain acute for some pollutants. In 2015, 22 out of 28 EU countries reported exceedances of the 2008 Air Quality Directive (AQD, 2008) limit values, for O_3, NO_2 and/or Particulate Matter (PM_{10} and $PM_{2.5}$) (EEA, 2015). While air quality exceedances were in the past widespread across Europe, they now tend to be restricted to specific regions like the Po Valley, the South of Poland area or Benelux for PM, and cities for NO_2 (Kiesewetter et al., 2013). Countries and regional authorities have the legal obligation of designing and assessing the impacts of air quality plans whenever exceedances occur but they generally lack the proper tools to do so (APPRAISAL, 2013).

Since the 80s modelling tools have been developed and used to support international negotiations on air quality in Europe. The GAINS-EU integrated assessment model (Amann et al., 2011) has been used to fix country-based emission reductions in order to achieve an environmental target in a cost-efficient way.

With the current situation characterized by regional and/or local (city) hot spots, EU integrated assessment modelling (IAM) needs however to be complemented by regional and local approaches. It is in this context that GAINS-EU was recently extended to cover city and street scales, on the basis of parametrizations based on finer-scale simulations and measurements (Kiesewetter et al., 2015). In some countries, national versions of GAINS, also based on finer scale modelling, have been implemented to balance regional and/or sectoral emission reductions in the most cost-efficient manner (e.g. GAINS Italy as in D'Elia et al., 2009). Similar tools, developed on the basis of different assumptions, have also been applied in some regions (e.g. RIAT, Carnevale et al., 2012) but their use remains limited. The same holds for dedicated city-scale IAM tools (e.g. BRUTAL, Oxley et al., 2009) that focus on local strategies.

The main purpose of IAM tools is to support policy makers in identifying possible actions in terms of air quality management. One particular issue is governance, namely the selection of the most appropriate and cost effective strategies within the area controlled by the policy makers. While some abatement measures clearly fall under European or country responsibility (e.g. EURO standards for vehicles), and others fall under the responsibility of city authorities (e.g. low emission zone for traffic), a wide range of measures remain in between those scales and require IAM tools to

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support decision-making on their selection and application.

The recent extension of GAINS-EU to cover the regional, city and street scales constitute a first step in this direction, but the approach remains country based and dependent of measurements. Other methodologies generally remain critically dependent on initial set-up assumptions that do not allow enough spatial flexibility to study this governance issue, i.e. to assess how the optimal abatement measures change with the size of the territory under consideration.

In this work we present a new approach to IAM focusing on regional and urban scales. We focus on the spatial flexibility of the approach to allow the assessment of contributions (in terms of emissions) from any regional area to air quality at a given location.

The methodology implemented in SHERPA to calculate the SRR relationships is first presented. A brief discussion about the modelling set-up is then provided before describing a specific example of use of SHERPA on London. The main purpose of this demonstration is to illustrate how SHERPA can support decision making in the field of air quality planning.

2. The SHERPA tool

The SHERPA tool (Screening for High Emission Reduction Potentials for Air quality) has been developed to address the following tasks:

(1) Source allocation: this step aims to assess the degree of control policymakers have on air pollution over their area. If most of the pollution is imported from outside their region, the policy makers have little control (and vice-versa). During this step, SHERPA provides information on (a) the amount of pollution originating from inside the region, detailed in terms of sectors and precursors and (b) the amount of pollution originating from outside the region.

(2) Governance: This step identifies the principal source areas (i.e. regions, countries) of the pollution at a location. Emissions from agriculture which require time to form secondary particulate matter will have a longer distance influence than traffic emissions that directly impact concentrations at the local scale. The SHERPA methodology is designed to identify and rank contributions (to air pollution levels) by all neighbouring and non-neighbouring regions for a specific sector of activity. This step sets the basis for fixing priorities in terms of regional collaborations that can increase the efficiency of abatement strategies.

(3) Scenario: The scenario analysis is the final stage in the process, once the activity sectors and their areas of origin have been identified. The policymaker then fixes the desired sector-specific emission abatements in terms of intensity and spatial coverage and tests their impacts on air quality levels.

These three steps which form the core of the SHERPA methodology are depicted in Fig. 1.

To address the objectives mentioned above, SHERPA needs to fulfill the following characteristics:

1) Spatial flexibility: i.e. the possibility of addressing emission abatement strategies over any given region or group of regions.
2) Speed: i.e. delivering fast responses to guarantee interactivity during the decision support process.
3) Light set-up: The simplified source/receptor relationships (SRR) that link emissions to concentration changes are based on a set of Air Quality Model (AQM) simulations. This phase should remain both simple (i.e. a transparent and easy to use methodology) and light in terms of the number of AQM simulations required to develop the SRR relationships.

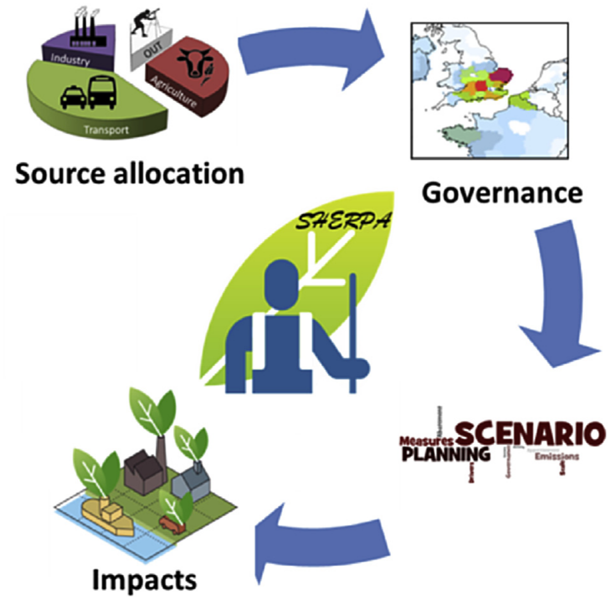

Fig. 1. Schematic overview of the three steps methodological approach followed in SHERPA. After the "source allocation", "governance" and "scenario" steps, impacts are computed. Details are provided in the text.

Spatial flexibility, speed and light set-up should be ensured while maintaining a high accuracy, i.e. SHERPA results should be in close agreement with the modelled AQM responses to varying emission scenarios.

3. Source/receptor relationships

3.1. Methodology

AQMs deliver pollutant concentration fields that account for the complex transport, diffusion and chemical processes in the atmosphere. The pollutant concentration in each grid cell is a function of varying emission contributions throughout the modelling domain. This approach is very accurate but requires too much calculation time to be useful in IAM tools which require interactivity to manage iterative requests. In addition, AQM approaches deliver information with a detailed time resolution that is not always used in the IAM analysis. A simplification is therefore made to reduce complexity, in particular the number of links between emissions and concentrations. One such simplification is to aggregate the emissions spatially (Clappier et al., 2015). In GAINS, emissions are aggregated on the basis of countries or regions and the relation between emission and concentration changes is assumed to be linear. The equations to be solved are then expressed as:

$$\Delta C_i = \sum_{j}^{N_{prec}} \sum_{K}^{N_{agg}} a_{i,j,K} \Delta E_{j,K} \tag{1}$$

where the delta concentration (ΔC) in a grid cell "i" is expressed as a linear combination of the aggregated emissions delta ($\Delta E_{j,K}$) ("agg") for each precursor ("prec"). The minimum number of simulations required to solve this system is equal to the product of the number of precursors by the number of aggregations. In general each unknown ($a_{i,j,K}$) is identified by performing a specific scenario in

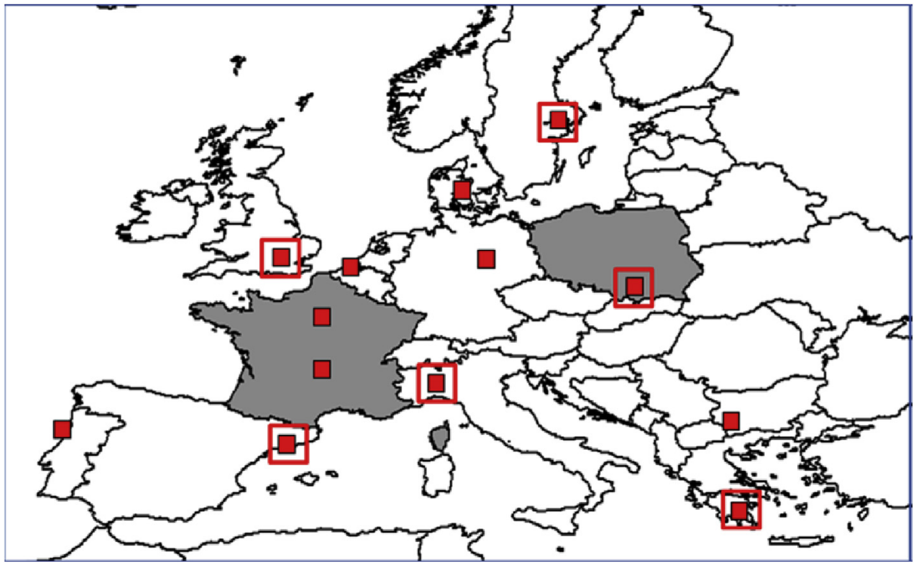

Fig. 2. Overview of the domains selected for the SHERPA evaluation. They include two countries (in grey), 6 regions (large rectangles – 140 × 140 km^2) and 13 local areas (small rectangles – 35 × 35 km^2).

which only the precursor "j" in aggregation "K" is modified. It is important to note that this does not constitute the only approach to solving system (1). Any other set of simulations could indeed be selected as long as the scenarios remain linearly independent from each other. It is also important to stress the fact that the a-priori selection of the emission aggregations (e.g. countries) limits the future application of the IAM to those same aggregations (or combination of these aggregations); and does not allow the subsequent consideration of areas smaller than the initial aggregations. The weights attached to the emissions from each grid cell (within a country/region) that contribute to the pollutant concentration at a given location are attributed during the training simulations and are assumed to remain valid for all scenarios. We refer to Clappier et al. (2015) for more details on these SRR aspects.

SHERPA also assumes a linear relationship between concentration and emission changes. This has been shown by Thunis et al. (2015a,b) to be a valid assumption as long as long-term (i.e. yearly or seasonal) concentration averages are considered, as in this work. In SHERPA the links between emission and concentration changes are computed cell by cell without any a-priori definition of emission aggregations:

$$\Delta C_i = \sum_{j}^{N_{prec}} \sum_{k}^{N_{cell}} a_{i,j,k} \Delta E_{j,k} \tag{2}$$

One of the main benefits of this approach lies in its spatial flexibility. Once the coefficients "a" are calculated, equation (2) indeed delivers the concentration changes resulting from emission changes applied over any geographical area, without the need to run specific additional simulations. A cell-to-cell approach, however, implies a large number of coefficients (a) to identify, leading to a prohibitive number of simulations (i.e. $N_{cell} \times N_{prec}$). To solve this problem the SHERPA formulation relies on the results of a statistical analysis performed on all available simulations (base-case and scenarios) over the entire modelling domain. This analysis showed that the correlation between ΔC_i (at one receptor cell "i") and $\Delta E_{j,k}$ (at source cell "k") decreases with "d_{ik}", the distance between these two cells ("i" and "k"). It has been assumed that the coefficients "a" in equation (2) follow a similar trend to this correlation and can therefore be approximated by the following distance-function:

$$a_{i,j,k} = \alpha_{i,j}(1 + d_{ik})^{-\omega^{i,j}} \tag{3}$$

where "i" is a grid cell within the domain in which the concentration delta is estimated, the indice "k" runs over all grid cells within the domain and "d_{ik}" is the distance between cells 'i' and "k". The two unknowns α and ω need to be defined for each precursor and each grid cell (i.e. 2*N_{prec} unknowns per cell). Even though relation (3) remains similar everywhere in the whole calculation domain, the values of α and ω are grid-cell specific. The parameter α is related to the amplitude of the function and provides information about the relative importance of one emission precursor with respect to another, whereas ω is related to the function width and provides information on the speed of decrease of the emissions impact with distance. The ω parameter depends on meteorological conditions, especially wind speed, and is also precursor specific (some emission precursors have longer residence times in the atmosphere).

With only two unknowns per cell and per precursor the number of equations requested to solve system (2) is in theory equal to twice the number of precursors. We however use slightly more simulations (between 15 and 20) to improve the robustness of the estimation of α and ω.

This methodology permits spatial flexibility in the definition of emission abatement zones while keeping a light training phase (only few AQM simulations are required). The cell-to-cell relationships however increases CPU time compared to other approaches but it is nevertheless manageable, taking 1–5 min to perform one scenario over Europe.

3.2. Model set-up

The SHERPA interface and tool can in theory be adapted to any region if fed with appropriate input data. By input data we mean (1) a gridded emission inventory detailed in terms of activity sectors and precursors (left to user choice) over the area of interest; (2) a series of 15–20 simulations performed with an AQM for a series of pre-defined emission scenarios to generate the SRR and (3) a correspondence table matching the user-defined shape files with the

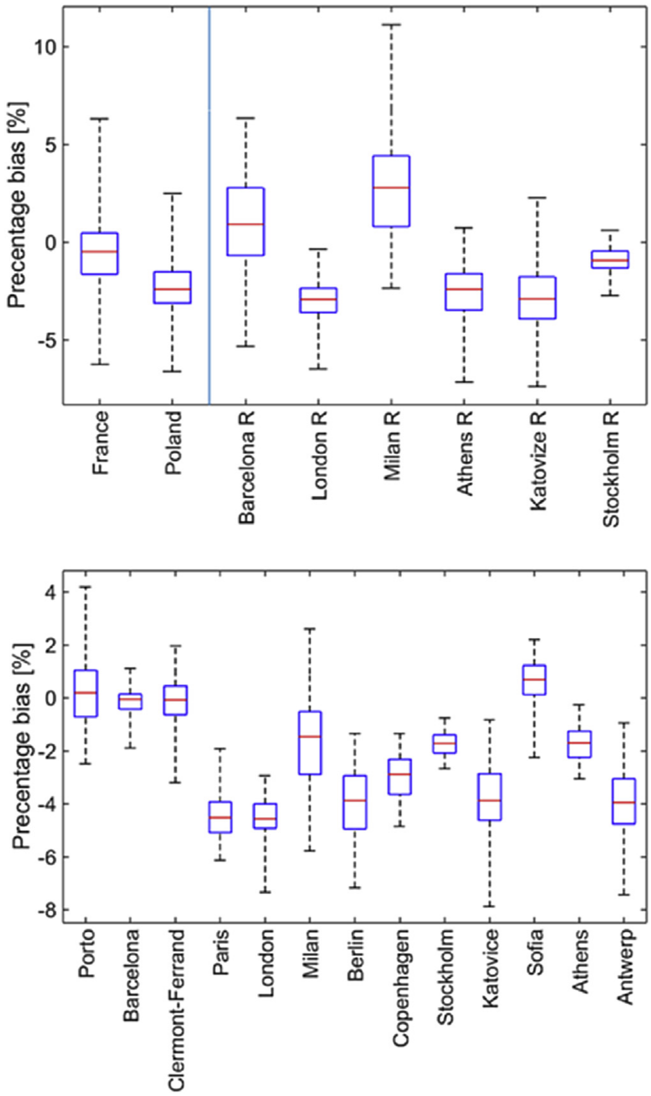

Fig. 3. Percentage bias computed for yearly PM_{25} concentrations (SRR-AQM)/AQM produced for different validation scenarios: top, from left to right, two scenarios where emission reductions are applied over one country (France and Poland) followed with scenarios where emissions are reduced over "regional" areas. Bottom: scenarios where reductions are applied over "local" areas (bottom). All precursors are reduced contemporaneously in all scenarios. The box-plot shows the percentage bias calculated in the cells belonging to the different reduction areas. For each of these areas, the median (horizontal red lines), the quantiles (horizontal blue lines) and the maximum/minimum values (horizontal black lines) of the percentage biases are shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

emission grid cells. These shape files are then used to define the areas where emission reductions are imposed.

In this work, the CHIMERE model (Menut et al., 2014) is used to derive the SRR over the whole European territory with a spatial resolution of 7 × 7 km^2. The anthropogenic emissions underlying the model simulations are based on the MACC-TNO emission inventory (Kuenen et al., 2014), with residential sector emissions modified to account for the enhanced wood consumption at extremely low temperatures (Terrenoire et al., 2015). The meteorological input data is based on IFS (Integrated Forecasting System from ECMWF) for the year 2010. Finally the areas of interest (i.e. the possible control areas) are based on the European Nomenclature of territorial units for statistics (NUTS) covering the $NUTS_0$ (countries), $NUTS_2$ (regions) and $NUTS_3$ (province) levels.

3.3. Evaluation

Series of AQM simulations in which emissions are reduced over the entire modelling domain are used to derive the SRR. In a first series, emissions are reduced per precursor by 50% from their reference level while in a second series all precursors are reduced simultaneously with intensity ranging between the CLE (Current Legislation) and MFR (Maximum Feasible Reduction), as defined in the EC Thematic Strategy of Air Pollution review (Amann et al., 2014). This set of simulations, referred to as training, is used to calculate the values of the SRR coefficients (α and ω) for each grid cell and precursor.

For the evaluation, we consider annual $PM_{2.5}$ concentrations and its emission precursors (Primary Particulate matter (PPM), NO_x, SO_2 VOC and NH_3) in Europe. As we are particularly interested in testing spatial flexibility, the evaluation scenarios focus on emission reductions imposed both regionally and locally in different areas of the domain. In this example emission reductions are imposed over 2 countries, 7 regions (140 × 140 km^2) and 13 local areas (35 × 35 km^2) (Fig. 2) for precursors reduced independently or contemporaneously.

The evaluation is then performed by comparing the results of the SRR with the AQM for these specific emission reduction scenarios.

The comparison of the concentration delta (difference between base case and scenario) obtained with the SRR and the AQM model is shown in Fig. 3, for different evaluation scenarios. Emission reductions are applied over France, Poland, and the regional and local domains, with a level of reduction of all emission precursors of 60%. Similar validation tests have been performed for single emission precursors and show the same performance. SHERPA typically simulates air quality with a relative bias (compared to the AQM) of less than 5% in most validation areas (it may reach however 10% at some locations mostly mountains)).

It is interesting to note that equations (2) and (3) are based on a simple distance-relationship which ignores directionality. The evaluation tests show that this assumption is valid, regardless of the domain size over which emission reductions are applied and regardless of the geographical complexity. Although counter-intuitive, the limited impact of directionality might be in part explained by the use of annual averages metrics in this work, as well as by the AQM relatively coarse spatial resolution. High concentrations also tend to occur with low wind speed, when direction is less important.

4. Application

As mentioned in the introduction, SHERPA can be operated in three main modes: source allocation, governance and scenario. In this section we describe the application of the SHERPA methodology to London. The three aforementioned steps are applied and for each, key information is highlighted. The objective is to offer an overview of the SHERPA capabilities highlighting its potential to design and assess the impact of air quality plans, rather than to look into the details of the results and formulate explanations.

All output are delivered as gridded yearly averaged concentration maps, either in absolute or relative (delta between base case and scenario) terms. For this, we have restricted our analysis to yearly averaged $PM_{2.5}$, although results are also available for yearly averaged NO_2, and yearly averaged PM_{10}. As mentioned the SHERPA calculation time to perform one single calculation is on the order of a 1–5 min.

The first step of the methodology, i.e. "source allocation" quantifies the contribution of the individual control areas (area under the responsibility of a policymaker where emission

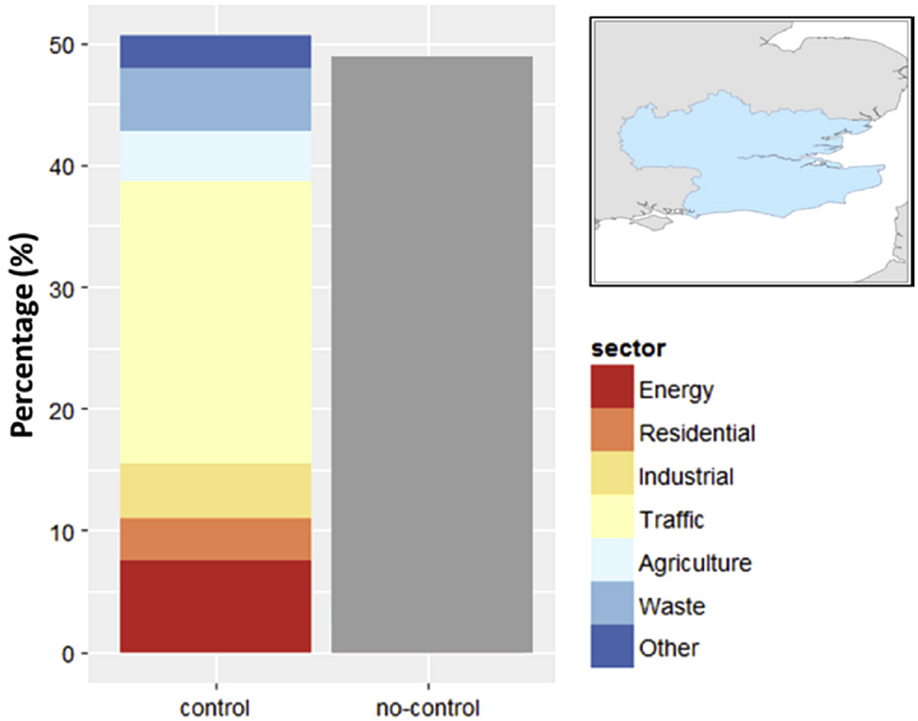

Fig. 4. Source allocation for the London Region (upper right corner), contributions are split between "control", i.e. the part which can be reduced via emission reductions in the control area and "no-control", the remaining part. Only the controllable contributions are split sectorally.

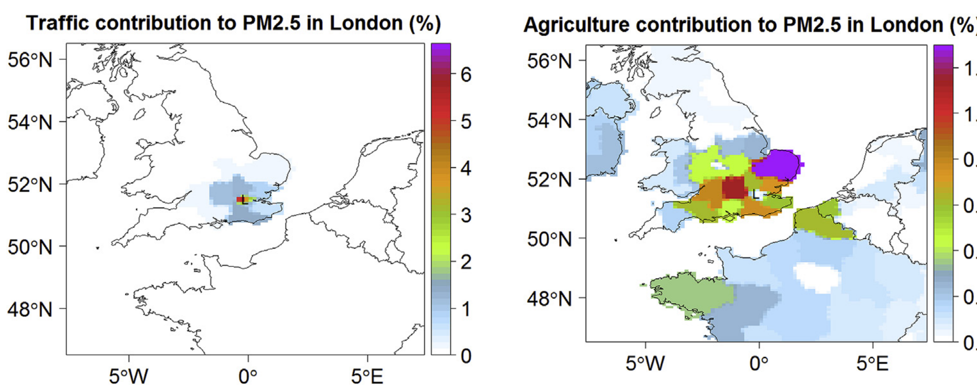

Fig. 5. Percentage contributions from emissions from each $NUTS_2$ entity to $PM_{2.5}$ concentration in London city center, for traffic (left) and agriculture (right).

abatement can be imposed) on $PM_{2.5}$ concentration levels at one given location in the center of London. In this application the control area is the London region defined as a combination of $NUTS_3$ entities (Fig. 4). During this phase the sector contributions are quantified within the control area. All SNAP categories are explicitly considered. The results (Fig. 4) show that roughly 50% of the $PM_{2.5}$ concentration can be abated by local emission reduction strategies. Improvement can in particular be obtained with local actions on transport (potential concentration reduction of 23%) and energy/industry (approximately 13% together). Agricultural and residential emissions are not key contributors at the local scale. The left column in Fig. 4 shows the non-controllable $PM_{2.5}$ pollution which results from (1) pollution that originates from outside the control area; (2) natural (dust, sand …) and (3) shipping (not considered in this work in the anthropogenic sources). The no-control fraction amounts to approximately 50% (grey area) in the case of London.

The second step of the methodology, i.e. "governance analysis" is performed to better understand the "no-control" fraction, in particular its sectoral split and its origin.

Fig. 5 shows the contribution from emissions from each $NUTS_2$ entity in Europe (only a zoom on the London area is shown here) to $PM_{2.5}$ concentration in central London. Fig. 5 (left) shows the contribution from emissions (mostly NH_3) in the agriculture sector. Impacts are mostly due to emissions outside of the London control area, highlighting the need of coordinating strategies not only with surrounding UK regions but also with other countries (i.e. France, Belgium, Netherlands, etc …). By comparison, traffic emissions (Fig. 5, right) have a predominant impact on the London and the immediate surrounding $NUTS_2$.

Fig. 6 results of repeating the analysis described above for each macro-sector. A complete overview of the various contributions to $PM_{2.5}$ in London is obtained in terms of activity sectors (x-axis) and geographic entities (varying colors). The most influential sectors

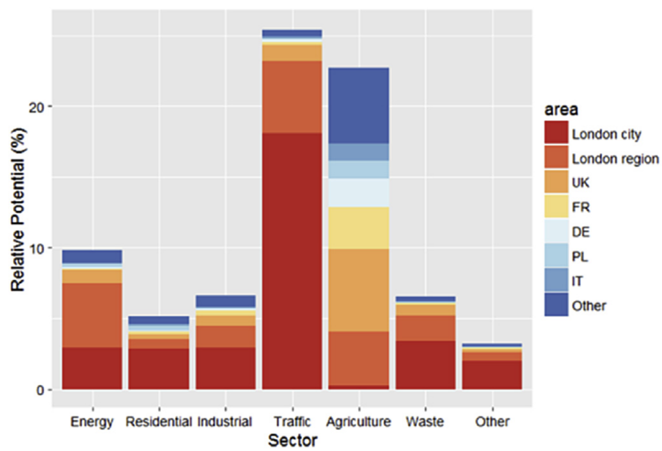

Fig. 6. Complete "source allocation and governance" analysis, where the contributions to the "London air quality" are split in terms of sectorial reductions (x-axis) and geographic entities reductions (colors).(For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

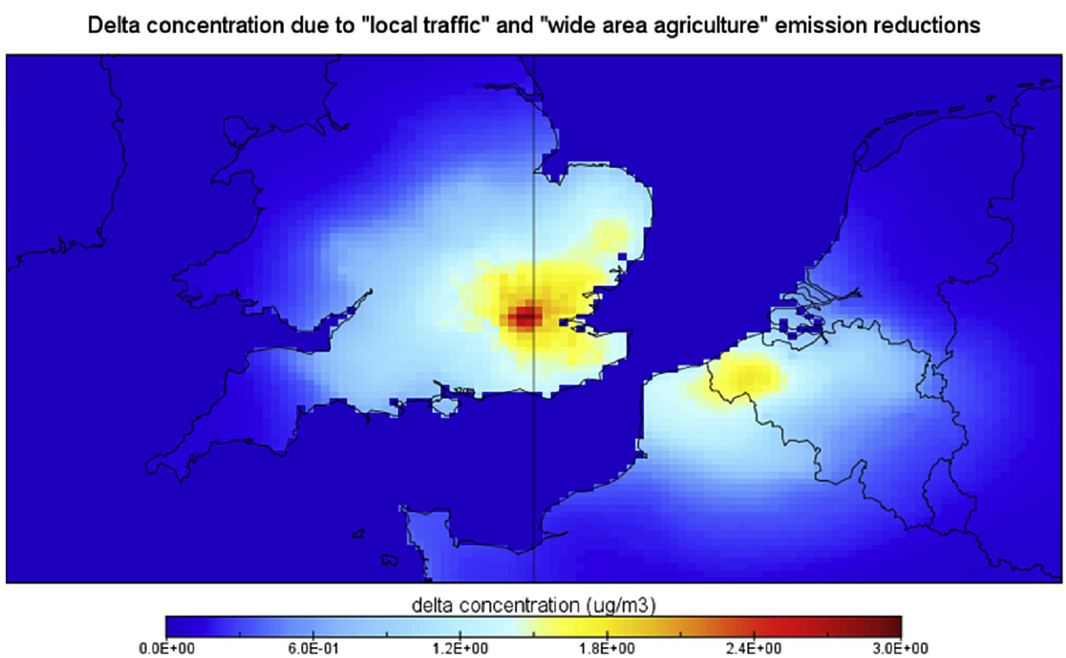

Fig. 7. Delta $PM_{2.5}$ concentrations (μg/m^3) obtained with SHERPA for a scenario focusing on local traffic emission reductions and agricultural emission reductions over a wider area including parts of neighbouring countries.

are named explicitly (energy, residential, traffic, agriculture …) while the remainders (solvent industry, fossil fuel extraction/distribution and other transport) are labeled as 'other'. As discussed above, the contribution from traffic is important at the city and region scales, whereas agriculture would require national and/or international action.

The final step of the methodology consists of designing a scenario and implementing it. Based on the two first phases (source allocation and governance) but also on his knowledge of the available emission abatement strategies, the policy maker is in position to design a "fit-for-purpose" scenario (in terms of emission reduction categories to be tackled, and geographical entities to be included in a coordinated action) to check its effect on air quality via SHERPA.

As we do not know a-priori the range of abatement strategies available to a policymaker in London, we use a hypothetical scenario to illustrate this functionality. The scenario is based on the main findings of the source allocation and governance steps and consists of (1) reducing the traffic emissions locally (i.e. London region) and (2) reducing agricultural emissions in the most influencing neighbouring NUTS (UK regions, France, Netherlands …). Emissions in both sectors are reduced by 50%. The results on concentrations levels are shown in Fig. 7.

5. Uncertainties and limitations of the approach

One of the current limitations of the approach is the spatial resolution (7 km) of the CHIMERE simulations underlying the SHERPA calculations. Small $NUTS_3$ entities might not be resolved well enough.

As mentioned when discussing the derivation of the SHERPA SRR, a linear response between concentration and emission changes is assumed. This implies that both the single non-linearities (e.g. a doubling in the emission reduction for NO_x would not result in a double impact in terms of concentrations) and non-linear interactions among pollutants (e.g. a sequential reduction of NO_x and VOC would not result in the same as reducing both precursors simultaneously) are neglected. As shown in Thunis et al. (2015a,b) this assumption is valid when long term (yearly or seasonal) averages are considered as in this work. It must be noted that most of IAM work (referred to in the introduction) relies on similar assumptions.

Obviously the SHERPA results strongly depend on the model used to define its SRR. The main advantage of the proposed methodology, however, lies in the limited number of AQM simulations requested to define these SRR. New simulations at the EU level can therefore be implemented relatively easily to test the robustness of the responses in terms of the modelling approach. In addition, robustness can also be assessed by comparing SHERPA responses to responses obtained in specific regional areas with other models, at the same or different resolutions. As such SHERPA serves as a benchmark to better understand model differences in terms of responses to emission scenarios.

The SHERPA calculations presented in this work are based on a single meteorological year (2010). While this year is thought to be representative of average meteorological conditions, the current set-up does not account for inter-annual variability. As mentioned above, the limited number of AQM simulations requested by this methodology would however allow investigating these aspects at limited cost.

Although not addressed with specific evaluation tests, SHERPA captures the impact of sectoral emission scenarios. Indeed emissions from different sectors only differ in the way they are spatially distributed and these spatial variations in the emission distribution have been shown to be well captured by the SHERPA methodology. This is however not true for point sources for which the release height becomes an important element. Additional simulations would be required to derive specific coefficients to address point sources.

SHERPA strongly depends on the quality of the underlying emission inventory. The issues raised in previous works (EC4MACS, 2013) regarding the distribution of wood burning emissions in French urban areas are a good example. Overestimating urban wood burning emissions will directly lead to overestimations in the source allocation, and subsequent identification of incorrect abatement strategies as a result of this misleading information. In this context the methodology presented in this work, which allows to fastly screen the links between emission and concentration changes, can be useful for detecting possible inconsistencies and supporting the improvement of the underlying emission inventories.

6. Conclusions

At the regional and/or city scales, policy makers often lack proper tools to assess the impact of different strategy options on air quality. Of those tools that are currently available, they often lack flexibility as they do not allow the exploration of other options beyond those built-in at start, e.g. on the choice of pre-defined control area (e.g. countries or regions). The SHERPA tool has been developed with the aim of filling this gap, with a particular focus on spatial flexibility.

The proposed methodology is based on a cell-to-cell relationship, in which a simple distance-function links emissions to concentrations. The main advantage of this approach resides in its spatial flexibility as the cell-to-cell relation allows emission reductions to be applied a-posteriori on any geographical area, independently from the AQM training simulations. In addition, the training simulations are limited to 15–20 which makes it straightforward to set-up for any domain of interest. This light training and gain in spatial flexibility is obtained at the expense of speed, as cell-to-cell relationships imply a larger number of operations within the SRR. This time is however limited to one to 5 min on current desktop computers for any given scenario at the European scale. Because spatial flexibility was the main focus, the validation of the methodology focused on emission reductions applied to different areas of different sizes (countries, regions, provinces throughout Europe) for precursors reduced independently or contemporaneously. All runs showed the accuracy to be high (relative bias around 5% with peaks at 10% in mountainous areas). The methodology is currently developed for yearly averaged PM_{25}, PM_{10} and NO_2.

The SHERPA three-steps methodology (source allocation – governance and scenario analysis) has been applied in London to illustrate how this tool could support decision makers in prioritizing interventions (in terms of macro-sector and pollutants) and in coordinating measures across governance levels.

The SHERPA tool will further be developed to assess its robustness in terms of the underlying model approach, emission inventory and meteorological variability, by repeating simulations with different models, inventories or meteorology. Further developments will also focus on the downscaling of air quality maps at 1 km resolution.

Given the possibility of feeding the SHERPA interface with other type of data (e.g. bottom-up regional emission and air quality modelling datasets), one main objective will be to compare the responses presented in this work with other methodologies at similar locations. In this sense, SHERPA can be seen as a potential means of fostering harmonization in the field of model evaluation, especially where models are used to assess the impact of emission scenarios on air quality.

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